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ACTIVELY CONTROLLED AFTERBURNER FOR COMPACT WASTE INCINERATOR

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ABSTRACT

Active control of fluid dynamics has been used to enhance mixing in incinerator afterburner experiments and increase the DRE for a waste surrogate. Experiments were conducted in a 50 kW scale burner in two configurations: one with direct modulation of the fuel and waste, referred to here as the gaseous burner (GB), and another with indirect modulation of starved air pyrolysis surrogate (afterburner, AB).

The open loop active control system is based on the concept of combustion in periodic axisymmetric vortices. Acoustic excitation was used to stabilize coherent vortices in the central air flow of a dump combustor like configuration. The fuel and waste are injected annularly at the dump. In the GB configuration, acoustic drivers modulate the fuel injection directly. In the AB configuration, the pyrolysis surrogate is modulated indirectly by periodic entrainment created by roll-up of the main air vortex, as well as acoustic excitation of secondary air injection. In both cases the phase angle is controlled such that the combustibles are introduced into the air vortex at the right time during the vortex formation. This leads to good mixing, a controlled yet lifted partially premixed flame, high DRE and low emissions.

We report scale-up and optimization of this control concept to the 50 kW level. It was found that a gaseous fueled actively controlled 50 kW incinerator simulator, designed on the same fluid dynamic principles as a 4.5 kW device, was able to surpass 99.999% DRE (destruction and removal efficiency) even when the waste surrogate (gaseous benzene, number three on the EPA list of hard to destroy hazardous wastes) constituted 17% of the total fuel content. This was with a combustible to total air ratio $\Phi = 0.78$. The GB configuration exceeded 6500 kW/m^3 for 99.99% DRE of benzene. The controller also reduced emissions: CO dropped from 2900 ppm to as low as 2 ppm. Unburned hydrocarbons were also reduced significantly. NO_x was reduced by less extreme ratios: levels down to 12 ppm were observed. Parameters found critical to maintenance of high DRE in the GB tests were the forcing level of the fuel injection, the fraction of circumferentially entrained air, and the phasing angle of fuel injection with respect to the air vortex roll-up.

In the AB configuration the geometry of the waste entrainment and the forcing level of the central air vortex were paramount, with the secondary air level and forcing intensity of secondary importance. The system still surpassed 5 nines DRE and still drastically reduced emissions. Acoustic design of the combustor was also important and the DRE was higher, the flame more compact, and the emissions lower if an acoustic resonance of the combustor was excited and if this frequency were near the preferred mode of the central air jet. The acoustic design minimized mode beating and increased coherency.

INTRODUCTION

The interaction between turbulent mixing processes and combustion is important in many practical applications such as airbreathing propulsion systems, energy conversion power plants, hazardous waste incinerators and other chemical reactors and industrial processes. Studies of turbulent mixing during the last two decades established the role of organized coherent large-

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scale vortical structures in the mass and momentum transfer across the shear layer between two fluids in motion (1-3). It was further determined that by manipulating these structures it is possible to alter the mixing process. Active control methods were devised to enhance the spreading rate of the shear layer by mechanical or acoustic excitation of the initial shear layer, and thus accelerate the mixing between the two streams (4, 5).

The understanding of the mechanism governing turbulent mixing and their control was extended to turbulent combustion. New laser based diagnostic techniques (6) with high temporal and spatial resolution, which yield species-specific two and three dimensional maps of the combustion region, accelerated the process; the important role of controlling the large and small scale mixing on the combustion process was determined (7). Initial studies of combustion control focused on the problem of combustion instabilities. The numerous studies on the application of active control to suppress combustion instabilities were reviewed recently by Candel (8) and McManus et al. (9). Active control by shear layer excitation was applied to enhance energy release (10-13) and to mitigate the production of pollutants (14). Fluid dynamic control has also been applied to hazardous waste incineration (15, 16).

At the Naval Air Warfare Center (NAWC), China Lake, the work on active combustion control included open and closed loop control of small scale-(~10kW) and large scale-(~1MW) combustors to enhance their performance by increasing energy release, extending the lean flammability limit, and stabilizing the combustion (17). The focus of the investigations shifted recently to emphasize practical applications such as the investigation of techniques for the development of compact waste incinerators for use aboard Navy ships. The common underlying concept of the combustion processes discussed in the present paper is vortex combustion. In practical combustors, the combustion process occurs at different locations within the combustion chamber depending on the air/fuel mixture and the fluid dynamic and thermodynamic conditions. Even if the average conditions are proper, it is common that the local conditions are not right for efficient combustion. The vortex combustion technique ensures that the combustion is confined to regions (i.e., vortices) within the combustor where optimal local conditions can be maintained. The vortex provides intense mixing and long residence time necessary for a complete combustion process. It also ensures localized high temperature to maintain efficient combustion. The fuel injection system can be designed for optimal utilization of the fuel by placing the fuel at the regions which provide the best conditions for its combustion. The purpose of the present paper is to study the method of synchronized liquid fuel injection into air vortices, and its use for gaseous and liquid waste incineration.

EXPERIMENTAL

The waste surrogate chosen was benzene, which is third on the EPA list of thermally stable, difficult to destroy hazardous compounds, as reported by Lee et. al. (18). Gaseous benzene was introduced into the GB or AB systems by bubbling flow through a bottle of liquid benzene in a temperature controlled water bath. The fuel was ethylene and the pyrolysis surrogate was a mixture of nitrogen, ethylene, and benzene at 62%, 31%, and 7% by weight. In all the incinerator tests reported here, the benzene constituted about 10 to 17% of the combustible content.

The larger scale incinerator (Fig 1), a direct scaleup of the 4.5 kW laboratory unit, was gaseous fueled and generated 47-70 kW of heat release. The inlet diameter was 38.4 mm and the dump 178 mm. The velocity of the inlet jet was 10.3 to 15.3 m/s for a Reynolds number of 26,000 to 39,000 based on the jet diameter. The measured preferred mode of the jet at 15 m/s was 190 Hz. The inlet flow was forced using a high speed acoustic valve (Ling Electronics™), and despite the order of magnitude increase in flow rate over the laboratory combustor, and nearly an order of

magnitude increase in Reynolds number, it was easy to generate coherent vortices using less than 5 Watts, as shown by Mie scattering flow visualization in Fig. 2. The acoustical output power of the Ling™ valve increases sharply with increasing flow rate, even at constant electrical power input, so much larger incinerators could be controlled with similarly modestly powered controllers.

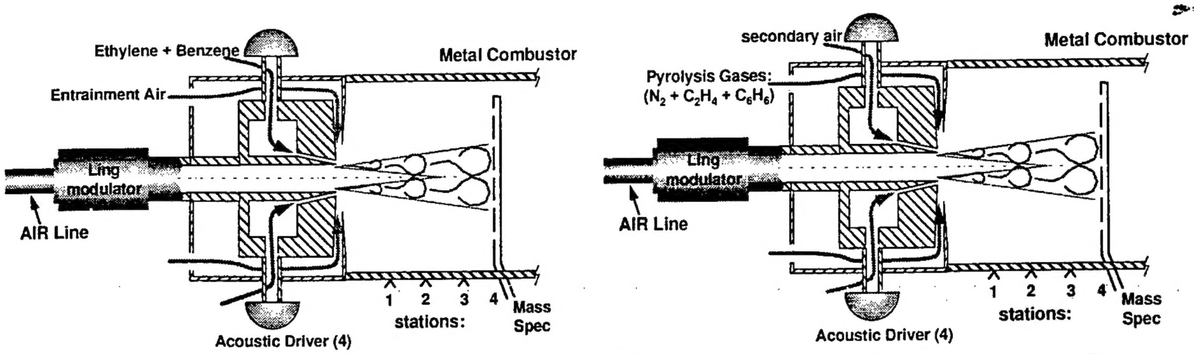

Fig. 1 Schematic diagram of the 50 kW actively controlled dump combustor incinerator afterburner concept: (a, left) Gas Burner (GB) configuration, (b, right) After Burner (AB) configuration.

In the GB tests the gaseous fuel and benzene were introduced circumferentially through 38 holes of 2.3 mm diameter fed from an acoustically forced plenum as in the smaller scale incinerator. The plenum is forced with four 75 Watt acoustic compression drivers (they aren't driven beyond 35 Watts, however). Extra "entrainment" air was introduced circumferentially, and at right angles to the central air flow, via an entrainment plate. This region is not directly forced, but PIV results reported last year (19) showed the entrainment is periodic due to the periodic roll-up of the central air vortices. In the AB configuration the entrainment region had a mixture of nitrogen, ethylene, and benzene, to simulate the output of a primary pyrolysis chamber such as a kiln or plasma unit. In this configuration what were the "fuel" jets in the GB configuration were supplied with secondary air instead, and no co-fuel was used. This flow was still acoustically forced, however. The main difference between the GB and AB configurations is that the combustibles are directly modulated by speaker drivers in the GB configuration. If these combustibles were the fuel rich pyrolysis output of a primary chamber, however, they would be hot and the speaker drivers may not be able to survive. This prompted the AB configuration studies where the speakers are not subjected to what would be hot gas.

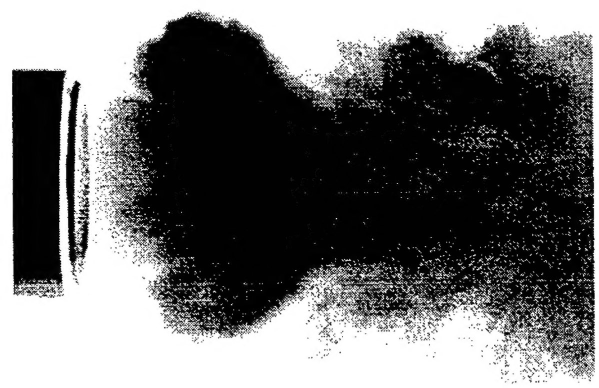

Fig. 2 Copper vapor laser planar Mie scattering image of the coherent vortex produced in the larger scale dump combustor incinerator via acoustic forcing; flow is left to right.

The remaining benzene in the exhaust was monitored with an on-line mass spectrometer tuned to m/e = 78. The probe was water cooled and several orifices averaged over the radial profile of the exit. The DRE (destruction and removal efficiency) was calculated from the benzene concentration remaining in the exhaust: DRE(%) = 100 x [1 - (benzene out/benzene in)]. DREs are also often quoted as "nines" where 99.99% DRE corresponds to 4 nines and DRE(nines) = $-\log_{10}$(1 - DRE(%)/100)). The sensitivity limit of the on line mass spectrometer corresponds to DREs of

about 5 nines, depending on the amount of waste loading. This sensitivity was obtained by averaging over about 2 minutes per condition. It should be noted that a mass scan from 50 to 200 amu showed nothing but benzene when the DRE was low and nothing at all when the DRE was high, so even though subsequent tests were done monitoring only the mass of benzene the results are valid as the benzene is not just being converted to some other hazardous compound.

Another identical water cooled probe was directly attached to a continuous emission monitor which measured O_2, CO_2 (calculated), CO, NO, and NO_2. Each probe could be placed at one of four locations within the 610 mm long combustor so that measurements could be made at various downstream x/D distances where x is the downstream mm and D is the dump diameter, 178 mm. Both probes were mounted vertically to minimize sampling error caused by buoyancy, i.e. the multiple orifices of the probes averaged over a vertical radial profile across the duct.

RESULTS and DISCUSSION

GB Configuration

The lessons learned using the small laboratory scale incinerator were applied at the larger scale with over an order of magnitude scale up of flow rate and energy release. The laboratory experiments at 4.5 kW were done near an overall Φ (fuel to air ratio/stoichiometric ratio) of 1.0, and were finished before acquisition of the continuous emission monitor (CEM). Initial experiments in the GB configuration showed that the DRE optimized at a Φ near 0.8, possibly due to less than perfect mixing that might be associated with lower coherency from the much higher Reynolds number (Fig. 3). Figure 4 shows that the benzene DRE exceeded the EPA limit of 99.99% at an x/D of only 1.7. This corresponds to a power density of 6500 kW/m^3. The most important parameter for these tests was the forcing level for the fuel jets. When the air vortex is forced as well, the DRE is considerably higher and the phase angle between vortex roll-up and fuel injection becomes important (Fig. 5), as it was in the laboratory tests.

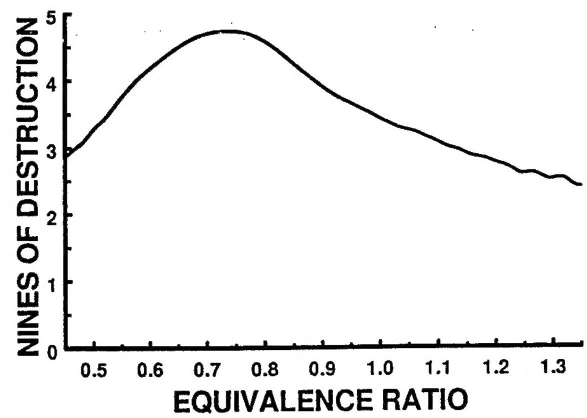

Fig. 3 Benzene DRE (in nines) in GB tests as a function of total stoichiometry.

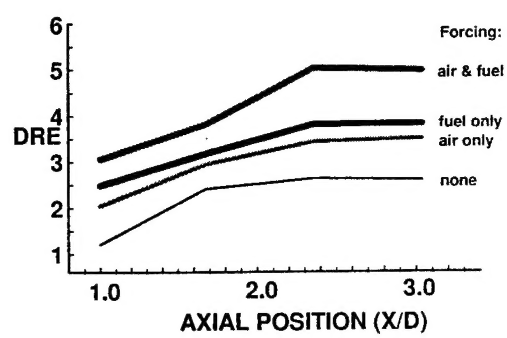

Fig. 4 Benzene DRE (in nines) as a function of axial position x/D (where x is the axial distance downstream from the dump and D is the dump diameter) for various conditions of the GB controller. The top curve is the entire controller optimized; the next down is for forcing of the fuel jets only; the next for air forcing only; and the bottom for no forcing at all.

These tests were done with a central air speed of 10.3 m/s and a forcing frequency of 120 Hz for a Strouhal number of 0.41. Both the central air and the fuel were forced at the same frequency (but not the same phase). The power was 47 kW. Subsequent tests were done at 15.3 m/s to get the frequency of the preferred mode of the jet up to match an apparent resonance in the combustor of about 190 Hz. This brought the power to 70 kW.

Measurements with the CEM showed that while the DRE for benzene was beyond 4 nines at x/D = 1.7, the emissions were unacceptably high. At the position of x/D = 1.7 the CO was as high as 10,000 ppm and the UHC were also quite high.

Obviously there was incomplete combustion despite the high DRE for benzene. Backing off on the Φ down to 0.6 from 0.8 caused the DRE to be similar, but the CO dropped to very low levels. At the exit (x/D = 3) the CO was as low as 2 ppm, the UHC below the detection limit of 0.01%, and NO_X about 20 ppm. The unforced combustor produced 2900 ppm CO, 0.19% UHC, and 65 ppm NO_X at the same position. This indicates that the controller not only increases benzene DRE and improves combustion efficiency, it also manages to reduce NO_X as well. In fact, changing the relative phase angle between fuel injection and vortex roll-up produces the same sine wave in CO and UHC (inverted) as it does in DRE, indicating that the mechanisms that improve DRE also decrease CO and UHC. With the controller off the flame is long and sooty; with it on it shortens, moves upstream, and is entirely blue.

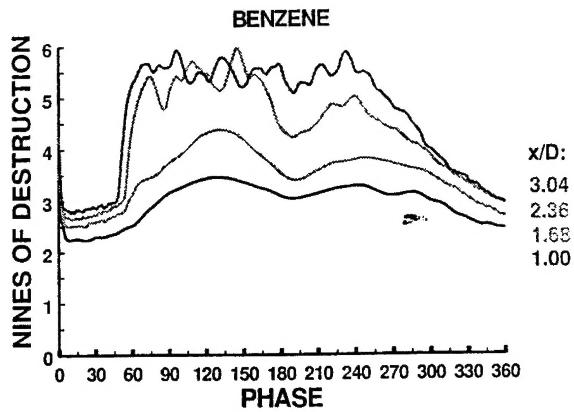

Fig. 5 Benzene DRE in the GB as a function of relative phase angle between the central air vortex roll-up cycle and the fuel/waste injection at various x/D locations as indicated.

The drop in the Φ brought the power back down to 49 kW despite the higher flow rate. The optimum fraction of secondary (entrainment) air in these experiments was 18% of the total air flow. The acoustic levels were quite high when the controller was operating. This is probably due to the modulation of the fuel into the vortices which creates periodic heat release, leading to acoustic energy, which then feeds back to enhance the coherence of the air vortex shedding process. There were complex interactions between the inlet mode, the combustor mode, and the preferred mode of the jet. Both the combustor and the inlet had resonances near 170 to 190 Hz and these changed as the temperature of the inlet air or combustor changed. The near equality of the resonances lead to undesirable beating in the acoustic intensity in the combustor: the pressure oscillations would periodically drop to near zero briefly. The beat was random but approximately a few Hertz. This is most certainly detrimental to the operation of the controller as it means there are intermittent periods of poor mixing and possible escape of benzene or production of burps of emission. Therefore, all subsequent tests were done with the Ling modulator valve close coupled to the dump combustor to place the inlet mode frequency out of the range of importance. The modulator was still easily able to generate coherent vortices and the acoustic modes were much simpler and more controllable. The acoustics in the chamber were also much more steady and the beating essentially entirely gone.

The combustor mode actually comes about due to a 46% area blockage at the exit by the mounting structure. This creates a "nozzle" at the exit. Variation of the length of the throat of this "nozzle" lead to changes in the combustor acoustic resonance frequency. These relative changes appeared to closely track the formula for a bulk mode oscillation. In fact, when the nozzle throat length was increased, the unforced system showed a clear peak in the acoustic noise level in the chamber. Bringing the forcing frequency near this peak caused an onset instability during which all the energy collapsed into a very coherent peak. If the forcing level were then dropped, the system would continue to self oscillate at a high level for quite some time. Under certain conditions, the acoustic level inside the combustor can reach 1 PSI peak to peak.

AB Configuration

In the afterburner configuration the combustibles are not directly modulated. Initial tests were done with the exact same geometry of the GB system with secondary air entering through the "fuel" jets and the N_2 ethylene benzene mixture entering what was the entrainment air in the GB system. It was clear that the geometry was not optimized for the AB operation. An extensive variation of the entrainment geometry was undertaken with the radius and velocity being varied and the performance evaluated by measuring the CO, UHC, and NO_x. In the best configuration, the pyrolysis surrogate was introduced much closer to the shear layer and the gap was reduced so it entered at a higher velocity (5 m/s vs. 1.8). With this geometry the entrainment plate just partially covered the secondary air jets (which are modulated acoustically using the same plenum used for the fuel in the GB tests). This closer coupling undoubtedly both enhances the injection of the pyrolysis surrogate gases into the shear layer as well as increasing the modulation level caused by the secondary air jets.

In this configuration the amount of secondary air flow was not of much importance and the CO was essentially as low for no secondary air flow as for values up to 20%. Note that even with no secondary air flow the plenum is still forced acoustically. However, the forcing on the central air flow becomes the primary controlling factor in this configuration: much larger drops in CO are obtained when the primary air forcing is increased than when the secondary is changed. Figure 6 shows the drop in CO as the primary air forcing is turned up (with the secondary forcing at maximum). The best performance still occurs with both the central and secondary air forced and

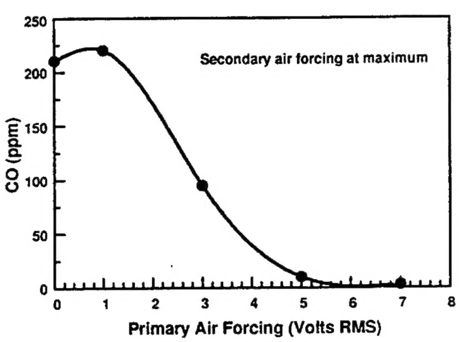

Fig. 6 CO (in ppm) versus central air forcing level (Vling in volts RMS) in the original AB configuration.

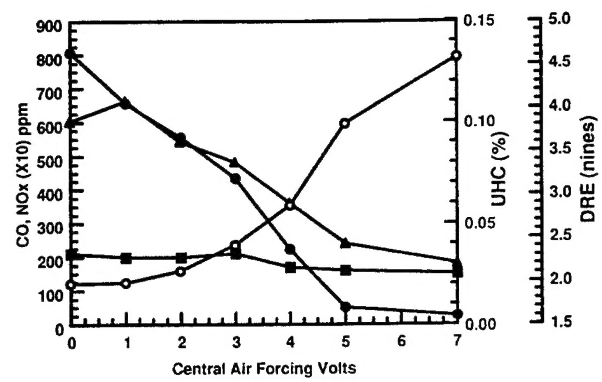

Fig. 7 Benzene DRE (in nines, right axis, O), unburned hydrocarbons (UHC axis on right, ▲), CO ppm (●), and NOx ppm times 10 (■) for the afterburner configuration shown as a function of forcing level on the controller. As control authority is exercised the benzene DRE goes up and the CO, UHC, and, to some extent, the NO_x go down.

the relative phase angle is still important. With the improper phase angle the CO was about 180 ppm and the DRE only 3.2 nines at x/D = 3. The unforced AB configuration gave CO of 1000 ppm and UHC of 0.14% all at x/D = 3. The best operation of the controller dropped CO to under 3 ppm and UHC to below 0.01% and raised the DRE to 4.5 nines. The NO_x for the unforced AB configuration, 20 ppm, was lower than the unforced GB configuration, but the controller reduced it further to about 12 ppm. As the forcing level on the primary air was increased the DRE increased as CO and UHC dropped (Fig. 7).

The GB configuration reached 4 nines DRE at x/D of only 1.7 and the DRE at x/D = 3 was 5.5. The initial AB configuration did not have DRE performance as good as the GB configuration. The

DRE reached only 4.5 nines at x/D = 3, the flame appeared to be not as compact, and the acoustic levels were lower. Apparently, without direct modulation of the combustibles there is less of a periodic heat release in the chamber, and perhaps less coherent vortices, leading to lower DREs. It was decided to redesign the entrainment region for optimum indirect modulation of the pyrolysis surrogate. The initial AB configuration had the entrainment region flow (pyrolysis surrogate) enter at 90° to the flow. It was thought that this may partially destroy the coherency of the vortex generation. It also did not match the GB configuration in which the combustibles (fuel + benzene) entered at 15° into the flow, and the secondary entrainment air entered at 90° but at a much lower velocity and much further from the exit dump.

Two modified entrainment/fuel injector plate assemblies were designed and tested. Both were designed to increase the modulation of the pyrolysis surrogate by the secondary air acoustics via internal mixing, and both redirected the mixture of pyrolysis surrogate and secondary air flow to enter the shear layer at 15° to the flow. The differences were in the details of the internal mixing region: one attempted to mimic an ejector, the other just mixed internally with a 90° intersection. This later version was found to be best and the results presented below are for it.

The redesigned entrainment/mixing geometry apparently was able to better modulate the pyrolysis surrogate as the chamber acoustic levels were much higher and the flame appeared shorter. Figures 8 and 9 show that the DRE performance was enhanced as well: the original AB configuration reached 4 nines only at x/D = 2.32 (Fig. 8) while the new version was somewhat more compact and reached 4 nines by x/D = 2.07. Figure 10 clearly shows that the new configuration is more compact and has better performance when CO is monitored. NOx levels were about 17 ppm.

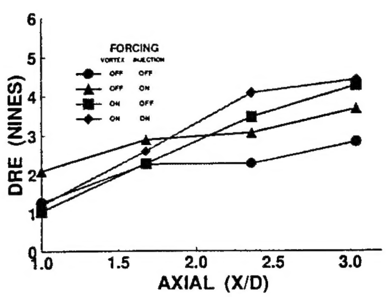

Fig. 8 Benzene DRE versus axial down stream distance (x/D) measured in the original AB configuration with various conditions of the controller (● is controller off, ▲ is secondary air forcing only, ■ is vortex forcing only, and ♦ is both forcing on).

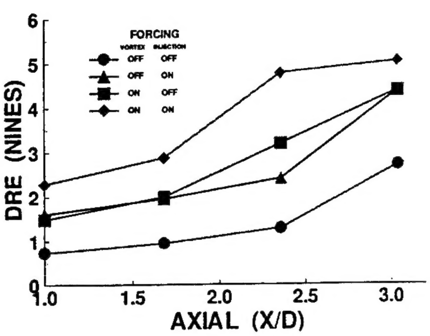

Fig. 9 Same as Fig. 8 for the optimized geometry AB configuration.

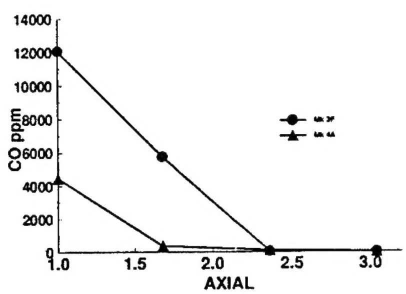

Fig. 10 CO (ppm) as a function of axial position (x/D) for the initial AB configuration (●) and the optimized configuration (▲). The optimized flame is clearly more compact.

Figures 11 and 12 show that the primary air forcing level still has the most effect on reduction of CO and increases in DRE. Fig. 13 shows that the secondary air forcing effect is not as dramatic. However, Fig. 14 shows that the DRE is still significantly increased when increasing the secondary air forcing level. This indicates that the new configuration better modulates the pyrolysis surrogate.

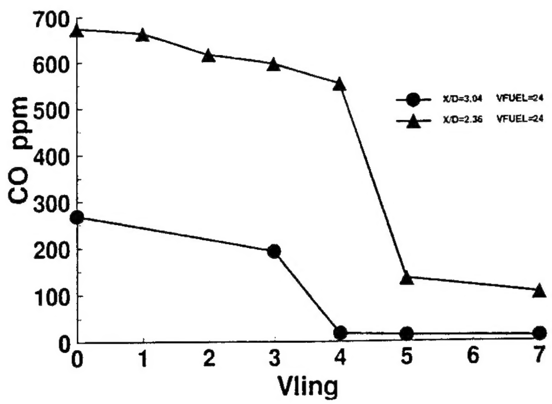

Fig. 11 CO (ppm) as a function of vortex forcing (Vling) for x/D = 3 (●) and 2.36 (▲) in the optimized AB configuration.

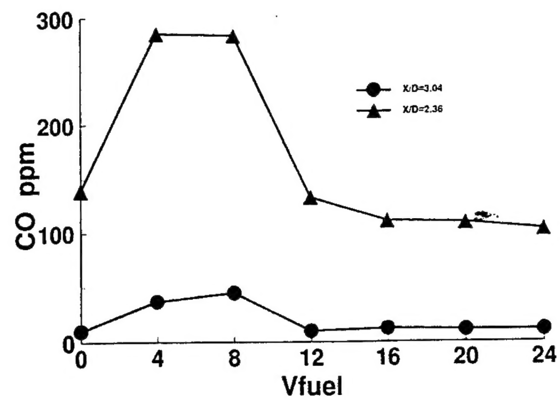

Fig. 13 CO (ppm) as a function of secondary forcing (Vfuel, volts RMS on the secondary air ports) for x/D of 3 (●) and 2.36 (▲) in the optimized AB configuration.

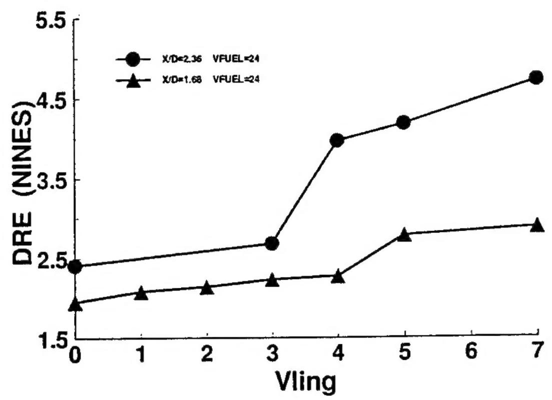

Fig. 12 DRE (nines) as a function of vortex forcing (Vling) for x/D = 3 (●) and 2.36 (▲) in the optimized AB configuration.

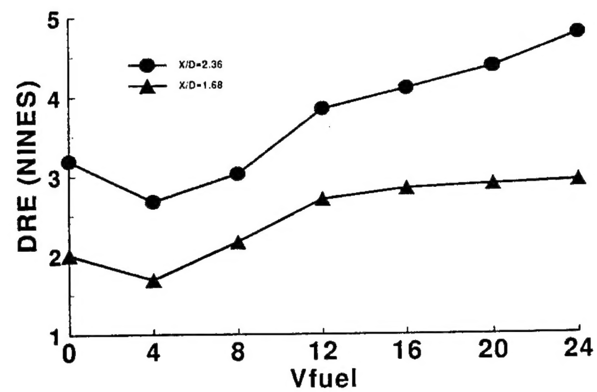

Fig. 14 DRE (nines) as a function of secondary forcing (Vfuel) for x/D = 2.36 (●) and 1.68 (▲) in the optimized AB configuration.

CONCLUSIONS

Active control of fluid dynamics has been used to enhance mixing in incinerator afterburner experiments and increase the DRE for a waste surrogate. Experiments were conducted in a 50 kW scale burner in two configurations: one with direct modulation of the fuel and waste, referred to here as the gaseous burner (GB), and another with indirect modulation of starved air pyrolysis surrogate (afterburner, AB).

The open loop active control system is based on the concept of combustion in periodic axisymmetric vortices. Acoustic excitation was used to stabilize coherent vortices in the central air flow of a dump combustor like configuration. The fuel and waste are injected annularly at the dump. In the GB configuration, acoustic drivers modulate the fuel injection directly. In the AB configuration, the pyrolysis surrogate is modulated indirectly by periodic entrainment created by roll-up of the main air vortex, as well as acoustic excitation of secondary air injection. In both cases the phase angle is controlled such that the combustibles are introduced into the air vortex at the optimal time during the vortex formation. This leads to good mixing, a controlled yet lifted partially premixed flame, high DRE and low emissions.

The concept was previously tested at the 4.5 kW level and was proven to be effective in reducing soot formation in propane, ethylene, acetylene, and benzene fueled flames. It was also shown to greatly improve waste destruction. Here we reported scale-up and optimization of this control concept to the 50 kW level. It was found that a gaseous fueled actively controlled 50 kW incinerator simulator, designed on the same fluid dynamic principles as the 4.5 kW device, was able to surpass 99.999% DRE (destruction and removal efficiency) even when the waste surrogate (gaseous benzene, number three on the EPA list of hard to destroy hazardous wastes) constituted 17% of the total fuel content. This was with a combustible to total air ratio $\Phi = 0.78$. The GB configuration exceeded 6500 kW/m^3 for 99.99% DRE of benzene. Emissions were seen to be high at $\Phi = 0.78$ so the stoichiometry was reduced to 0.57. Under these conditions the controller also reduced emissions: CO dropped from 2900 ppm without control to as low as 2 ppm with. Unburned hydrocarbons were also reduced significantly. NO_x was reduced by less extreme ratios: reductions of 3 to 5 were observed and absolute levels under active control were down to 12 ppm. Parameters found critical to maintenance of high DRE in the GB tests were the forcing level of the fuel injection, the fraction of circumferentially entrained air, and the phasing angle of fuel injection with respect to the air vortex roll-up.

In the AB configuration the geometry of the waste entrainment and the forcing level of the central air vortex were paramount, with the secondary air level and forcing intensity of secondary importance. The controller was still effective and DREs beyond 5 were easily attainable at x/D of 3.0 and the system exceeded 4 nines at x/D = 2.07. The controller also significantly reduced CO and UHC, and NO_x. Acoustic design of the combustor was also important and the DRE was higher, the flame more compact, and the emissions lower if an acoustic resonance of the combustor was excited and if this frequency were near the preferred mode of the central air jet. The acoustic design minimized mode beating and increased coherency.

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